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Issues Facing the U.S. Mirror Program

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Preface

In this document I have analyzed some of the current issues associated with the U.S. Magnetic Mirror Program. They are presented as five separate papers entitled:

1. Relevant Issues Broughtup by the Mirror Reactor Design Studies

2. An Assessment of the Design Study of the 1 MeV Neutral Beam Injector Required for a Tandem Mirror Reactor

3. The Significance of the Radial Plasma Size Measured in Units of Ion Gyroradii in Tandem Mirrors and Field Reversed Mirrors

4. Producing Field Reversed Mirror Plasmas by Methods used in Field Reversed Theta Pinch

5. RF Stoppering of Mirror Confined Plasmas

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I.

RELEVANT ISSUES BROUGHTUP BY THE MIRROR REACTOR DESIGN STUDIES

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Relevant Issues Broughtup by the Mirror Reactor Design Studies

I. Introduction

The conceptual studies of fusion reactors employing the magnetic mirror confinement concept are presently done at Lawrence Livermore Laboratory (LLL) and at the University of Wisconsin. Design studies of mirror fusio reactors have been carried out at LLL during the past several years. The prior studies on fusion reactors at the University of Wisconsin have been based on tokamak concepts. The present studies at LLL are centered around reactors based on the tandem mirror concept and the field reversed mirror concept which use high power neutral beam systems. The University of Wisconsin study considers radio frequency - heated tandem mirror reactors and it is expected to be completed by 1979. The goals of these studies are to provide conceptual engineering designs for every essential reactor components leading to cost estimates and specifically (1) to identify the relationships between plasma performance and system design and (2) to optimize the components and the system parameters for the design of commercially viable reactors.

II. Highlights of Previous Mirror Reactor Studies

The studies of both pure fusion mirror reactors and fusion-fission hybrid reactors which were carried out at LLL [1/] prior to 1976 were based on usin a single Yin-Yang confining magnetic mirror geometry and neutral beam injection. These studies concluded the following:

A. Pure Single Cell Mirror Fusion Reactors

For pure fusion reactors, because of their high power density and because plasma losses do not drastically increase with decreasing size, the mirror reactor can be made small. However, the rapid particle losses out of the ends makes a mirror reactor with classical end losses have a low Q-value (~ 1) and consequently more than 75% of the gross electrical power will have to be recirculated back to the neutral beam injectors.[2/] This makes the pure fusion reactors highly uneconomical compared to the present day nuclear power plants.[3/] Further increase in the Q-value is thus required for economic competitiveness with other options.

B. Single Cell Fusion-Fission Hybrid Reactors

The goal of fusion-fission hybrid reactors is primarily the production of fissile fuel at minimum cost in blankets containing uranium or thorium. The energy gain in the fusion-fission cycle overcomes the low-Q problem of the mirror fusion reactor. Such a reactor can produce fissile fuel for burner fission reactors[2, 3/] so that the overall system can be a more attractive net power producer.

In 1976 the direction of the mirror program at LLL was changed and LLL began exploring Q-enhancement ideas. The new efforts gave rise to the concepts of the Tandem Mirror Reactor and the Field Reversed Mirror Reactor. In FY 1977 LLL completed preliminary conceptual design of a Tandem Mirror

Reactor. This reactor consists of a long solenoid (100 m) containing a D-T plasma and standard Yin-Yang mirror cell at each end acting as electrostatic plugs. In FY 1978, LLL completed a similar conceptual design of a Field Reversed Mirror Reactor. These studies[4, 5] indicated that both these concepts can yield fairly high values of Q ($\sim$ 5 or more). The technology and physics issues raised by these studies form the program plan for the ongoing mirror reactor studies at LLL.

III. Current LLL Program Plan in Reactor Studies

Task A: Enhancement of Q and Power Density in the Tandem Mirror Reactor

Conduct a tandem mirror reactor design study emphasizing the key technology and physics issues raised in the FY 1977 study, such as:

- the plug injection energy
- the plug mirror ratio
- the mirror ratio between the plugs and the center cell
- the plasma β in the plug and in the center cell
- the central cell ion temperature
- tritium plug injections in place of deuterium
- higher plasma β in the center cell (assuming stability)
- higher plug plasma β (1-2)
- intentionally spoiling alpha-particle confinement
- the vacuum field strength at the center of the plug

- higher vacuum mirror ratio of the plug coil
- direct heating of electrons which necessitates less neutral beam injection in the end cell, etc.

The goals for a TMR are recirculating power less than 15% and wall loading of 4 MW/m^2 and maximum power output about 1000 MWe as specified by the D&T Program.

Task B: Reverse Field Mirror Reactor

Conduct a conceptual design of a Reverse Field Mirror Reactor emphasing:

- start up
- Ioffe bar
- mirror magnet
- blanket maintenance
- alpha-particle dynamics
- steady-state operation of the device
- obtain higher output power per cell

The goals for a FRMR are recirculating power less than 15% and wall loading of $4MW/m^2$, as specified by the D&T Program.

IV. Results of the Current Tandem Mirror Reactor Studies

The current program has arrived at a TMR reference design for a reactor producing 1000 MWe net electric power. The optimized parameters of the reference design are:

- Plug injection D^0
- Plug vacuum mirror ratio 1.07
- Plug plasma β 1.0
- Central cell plasma β 0.7
- Fraction of alpha particles adiabatically confined 1.0
- Plug vacuum centerfield 16.5T
- Blanket energy multiplication 1.2
- Thermal conversion efficiency 0.4
- Direct converter efficiency 0.6
- Injection efficiency 0.8
- Injection energy 1.2 MeV
- Central ion temperature 30.0 KeV
- Plug to central mirror ratio, R_{vac} 7.0

The study involved varying several input parameters in order to optimize the design. The results are given in Figures 1 thru 9. The optimization is always a tradeoff between a good power balance (lower recirculating power fraction) and a high central power density (high first wall neutron loading).

V. Results of the Current Field Reversed Mirror Reactor Studies

The current program has arrived at a reference design for a Field Reversed Mirror Reactor producing 74 MWe net electric power. The optimized parameters of the reference design are;

• Injection energy	~200 keV
• Injected power per cell	3.64 MW
• Ratio of plasma minor radius to ion Larmour radius	5
• Ratio of plasma major radius to plasma minor radius	2
• Ratio of plasma length to plasma minor radius	6
• Plasma beta	1.5
• Alpha-particle energy deposition	10%
• Electron temperature	31 keV
• Average ion energy	96 keV
• Q	5.5
• Fusion power per cell	20 MW
• Number of cells	11
• Blanket energy multiplication	1.2
• Direct converter efficiency	0.5
• Thermal conversion efficiency	0.4
• Injector efficiency	0.74
• $B_{o,\ vac}$	4.1T
• Axial magnetic well	1.0013
• Radial magnetic well	1.0001
• Mirror coil current	520 kA
• Ioffe bar current	280 kA

The basic assumption is that a stable field reversed plasma can be created and maintained by beam injection and that the plasma is in the form of a fat toroid with a minor radius of a few gyroradii.

A preliminary study showed that the fusion power from a single FRM cell is about 20 MW. To make the reactor more economically viable, present designs arrange a number of plasma cells on a common axis with sets of circular mirror coils between the cells in order to suppress the attractive force between adjacent plasma toroids. A set of 4 Ioffe bars passes through the reactor to produce radial magnetic wells in each cell to assure stability of the FRM plasma. The reference design requires 11 cells to produce 74 MWe of net electric power. Each cell would require neutral beam injectors providing 19A of 200 kV D-T atoms. The reactor is provided with two direct converters at each end to receive the energetic charged particles. To limit the power density below 100 w/cm^2 these converters, which are about 25 meters long, should be placed at least 60 meters from the center of the reactor. The design study involved optimization of various parameters such as a) the cross-sectional size of copper mirror coils and Ioffe bars (smaller coils produces larger resistive loss and larger coils induce proportionately larger neutron attenuation), b) cell length (very low cell length requires very large copper coil current and large cell length reduces the overall power density of the reactor), and c) the neutral beam injection energy (as the injection energy is increased Q increses and the fusion power increases while cost associated with the required higher magnetic field strength and copper

coil power loss increases more rapidly). The parametric study is shown in Figures 10 thru 12.

The design studies of both the Tandem Mirror Reactor and the Field Reversed Mirror Reactor, carried out at LLL have been fairly extensive and the reports of the findings are under preparation. The current studies made use of detailed physics calculations (based on yet to be proven physics assumptions) and attempted more complete engineering designs of the reactors. The detailed analysis covered many areas of concerns which were ignored in the previous studies such as the problem of ash (^4He) buildup and the fact that the field lines in the case of a field reversed geometry must be slightly "twisted" as in the stellator. The detailed parametric studies carried out in these studies will be of great value in assessing the technical feasibility and the economic viability of these types of reactors in the future. The general conclusion of the present study is that if the physics assumptions are valid and the technological requirements can be met, the TMR and FRMR concepts have strong reactor potentials.

VI. Relevant Issues Broughtup by the TMR and FRMR Studies

The issues which could challenge the credibility of the present TMR and FRMR designs are either (a) connected with the not so well validated physics of tandem mirror configuration or the field reversed mirror configuration or (b) connected with the stringent and unproven technological requirements associated with various components such as neutral beams. Furthermore, any physics or technological consideration which could improve

the Q (minimize the recirculating power fraction) and thereby-making the designs economically more attractive should also be very relevant. Such economic considerations should be based on not only the initial capital investment but also the reliability and maintainability of the device.

A. Physics Issues

The physics issues of the Tandem Mirror Reactor are primarily associated with the simple TMR physics model used in these design studies. This physics model relates the densities, energies, and containment times of the ions and electrons in the plugs and central cell through well understood principles, namely, standard mirror plasma potentials and electrostatic stoppering; but they have yet to be combined in an experiment. Hence, these issues form the basis for the Tandem Mirror Experiment under construction at LLL and can be related to the three physics objectives of the program.

- To demonstrate the establishment and maintenance of a potential well between two mirror plasmas connected by a solenoid confined plasma.
- To investigate the microstability of the plug-solenoid combination in order to maximize the plug density to injection power ratio.
- To develop a scalable magnetic geometry while keeping macroscopic stability at high beta.

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- To develop a scalable magnetic geometry while keeping macroscopic stability at high beta.

In a tandem mirror configuration, the requirement of quasi-neutrality establishes a potential difference ϕ_c between the plug and the solenoid regions given by

$$\phi_c = T_e \ln\left(\frac{n_p}{n_c}\right) \tag{1}$$

where T_e is the electron temperature (which is the same in both regions); n_p is the plug plasma density and n_c is the solenoid plasma density. Maintaining ϕ_c by controlling T_e, n_p and n_c is to be achieved by independently controlling the rates of injection of ions into the plugs and into the central cells; this is the first objective of the experiment.

The time required for the central cell ions with energies less than ϕ_c to diffuse upward in energy above the barrier height is given by

$$\tau_c = \tau_{ii}\, g(R) \left(\frac{T_e}{T_i}\right) \ln\left(\frac{n_p}{n_c}\right) \left(\frac{n_p}{n_c}\right)^{(T_e/T_c)} \tag{2}$$

where τ_{ii} is the ion-ion collision time $g(R) = \sqrt{\pi}\ (2R + 1) \ln(4R + 2)/4R$ T_c is the central cell ion temperature and $R = B\ (\text{mirror})/B\ (\text{solenoid})$. Thus, in order to maintain τ_c above τ_{ii} we require

$$\frac{n_p}{n_c} > 1 \tag{3}$$

and

$$\frac{T_e}{T_c} > 1 \tag{4}$$

Maintaining a high value for n_p should be intrinsically related to the loss mechanisms observed in the 2X-IIB experiments. Since the present TMR designs assume that the existing mirror theory is applicable to the tandem mirrors this assumption has to be experimentally verified.

The assumption that the Q-value of the tandem mirror geometry can be arbitarily increased by increasing the volume of the central cell compared to the volume of the plugs is very advantageous. However, the system may be subjected to microinstabilities assoicated with mirror plasmas. Further, there exists bad magnetic line curvature at the transition between solenoid and plugs. The anticipated MHD instabilities are the flute-interchange mode in the system as a whole and at high β ($\gtrsim$ 0.5), the finite β mirror mode in the plug, and ballooning and interchange modes in the solenoid. The suppression of such instabilities needs to be demonstrated experimentally to validate the present TMR designs.

The TMR design studies assume negligible electron thermal conduction and end cooling, also need to be experimentally demonstrated.

The build up of alpha particles within the solenoid was not considered in the present TMR study. Cross field transport or selective leakage of alpha-particles should also be considered.

The fundamental issues upon which the viability of the Reversed Field Mirror Reactor concept depends, also fall in the area of physics, much the same way as for the tandem mirror concept.

Field reversal, although demonstrated in theta pinches[6/] and relativistic electron rings[7/], is yet to be demonstrated in a mirror geometry. Creations and sustenance of such a configuration in Beta-II or MFTF is, hence, a most important issue. The theory of the concept itself is not yet proven. Hence the present physics understanding cannot yet offer much confidence in the physics models assumed in the design studies.

B. Technological Issues

The stringent technological requirements imposed on the performance of various components are often beyond the present engineering capabilities. The reference TMR and FRMR designs require 1.2 MeV and 200 keV respectively steady-state deuterium neutral beam sources with substantial current outputs. The high power neutral beam sources so far produced can be operated only in pulsed modes. To establish the economic viability of advanced neutral beam sources which can be operated continuously require a great deal of time, money and effort. None of the injectors presently being designed or built are capable of continuous operation. Sources which can be operated on a steady-state basis will truly be an engineering challenge.

Neutral beam technology up to the one hundred keV range is based on the production of accelerated positive ions and their neutralization. The neutralization efficiency of positive ions in the hundreds of keV and MeV ranges is very poor as compared to negative ion beams; but the negative ion source technology is not at all well developed. Since they are essential for TMR and FRMR, an accelerated effort in negative ion beam technology is warranted.

The present study assumes the efficiency of the direct converter to be 0.6. Although there exist direct converters with higher efficiency, the question is whether a reliable and rugged direct converter, which may have to function continuously under reactor conditions (high particle energy and power density) can have such high efficiency. Experimental evidence is needed to justify this assumption. Locating the direct converters at the ends such that they do not interfere with the functioning of the reactor (neglible end cooling through electron thermal conduction) may pose another problem in TMR. Reliability of components such as electrical insulators and properties of materials under reactor conditions will have to be known before credible designs can be made.

The ability to design and build large NbTi magnet coils such as those required for hybrid reactors (22 m diameter), field reversed mirror

(6 m diameter), and central cell of TMR (9 m diameter) and which have modest field strengths (8T, 4.1T and 2.4T, respectively) needs to be developed.

The TMR reference design calls for a plug vacuum center field of about 17T. Hence, it is necessary to develop the ability to design and build such high field strength coils (using Nb_3Sn superconductor) where the magnetic force restraint problem is a primary concern.

VII. Innovative Ideas

The third relevant area is concerned with innovative physics or technology ideas which could improve the Q or reduce stringent technological requirements on components.

Direct heating of electrons in the TMR would reduce the required neutral beam injection energy in the end cells. The present study[4/] shows that, if the fraction of the total heating that goes directly into electron heating is 0.75, the required optimum neutral beam energy is about 500 keV (less than half of what it was without electron heating).

Ion-cyclotron resonance heating in TM plugs as a means for reducing neutral beam energies have also been suggested[8/]. Initial studies show that a constant density can be maintained with half injection energy, doubled current, and 25% ICRH power[9/].

Re-assessing the trade-off between the requirements imposed on blankets and injectors in the present study showed that a cheaper blanket would require more expensive injectors but the Q value can improve as much as 50% for a 5% cost increase [10/].

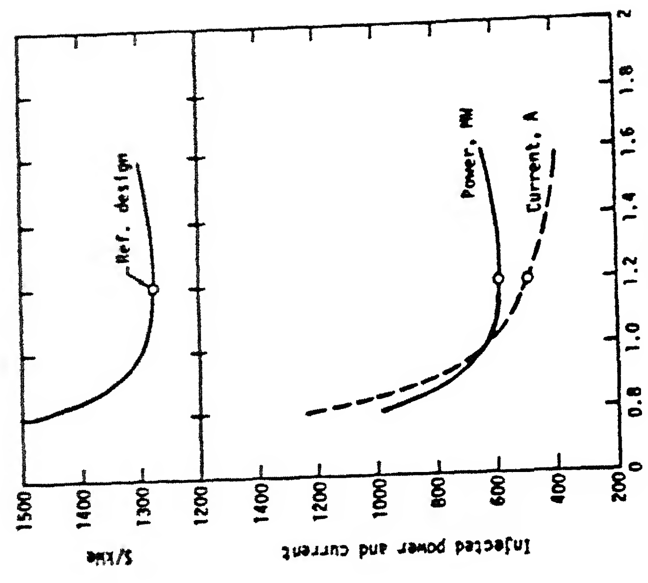

Figure 2

THR Cost vs Injection Energy

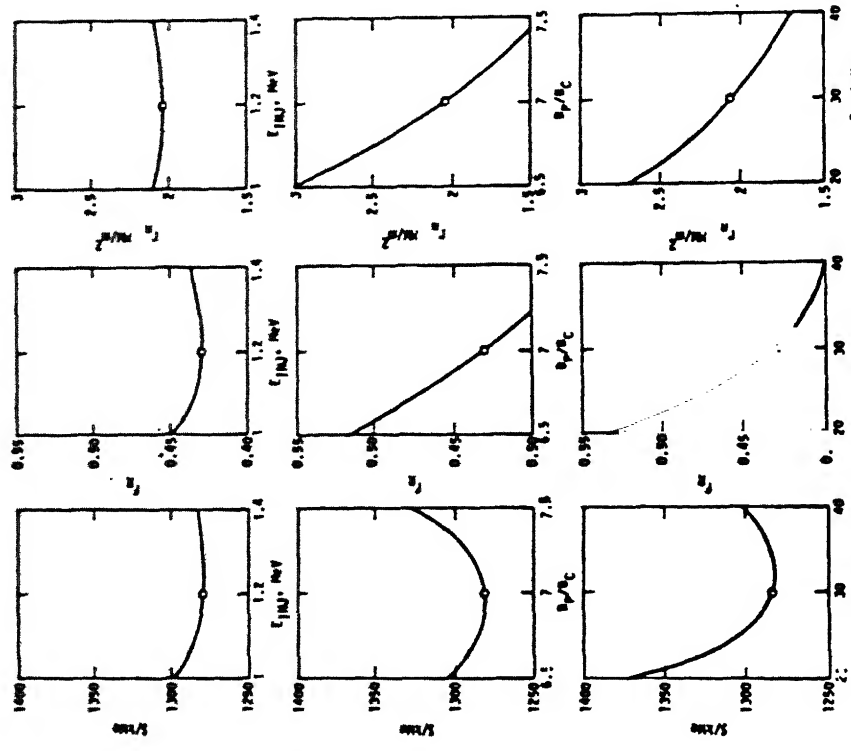

Figure 1

Optimization of the 1000 MWe THR

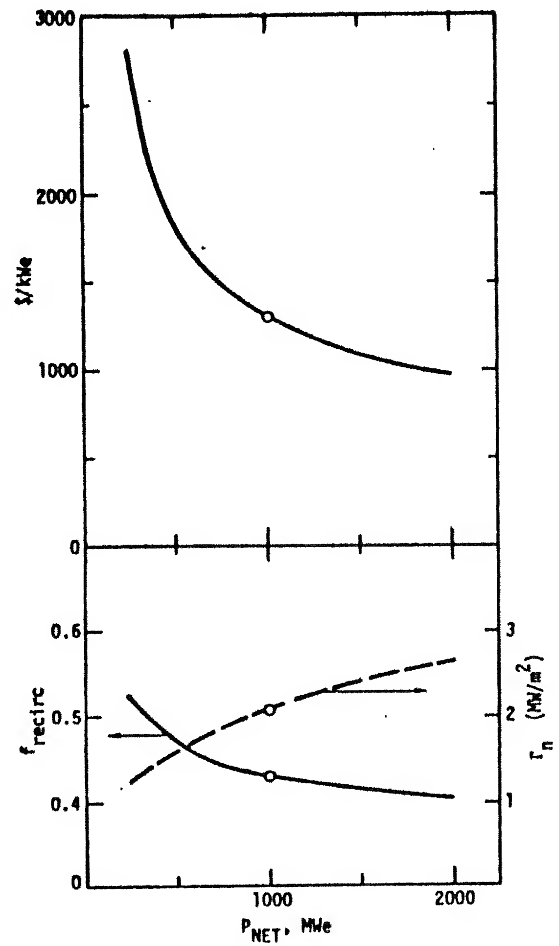

Figure 3

THR Cost vs Power Output

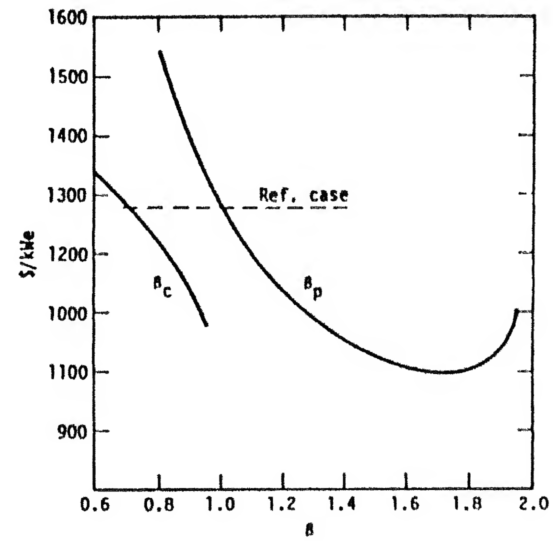

Figure 4

THR Cost vs Beta

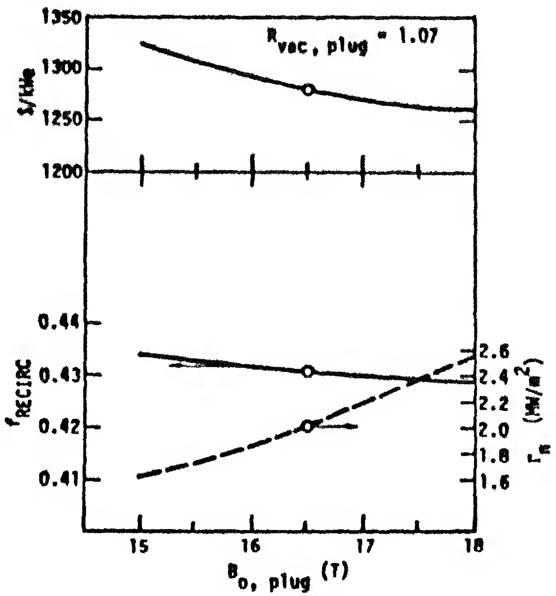

Figure 5

TMR Cost vs Plug Field Strength

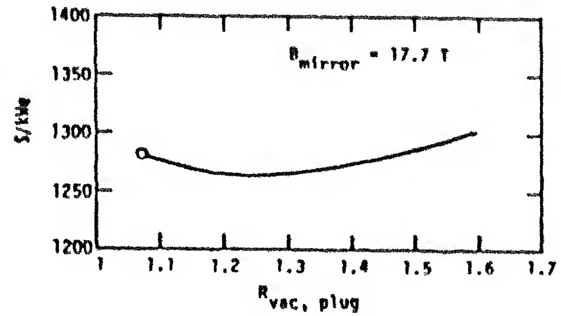

Figure 6

TMR Cost vs Plug Mirror Ratio

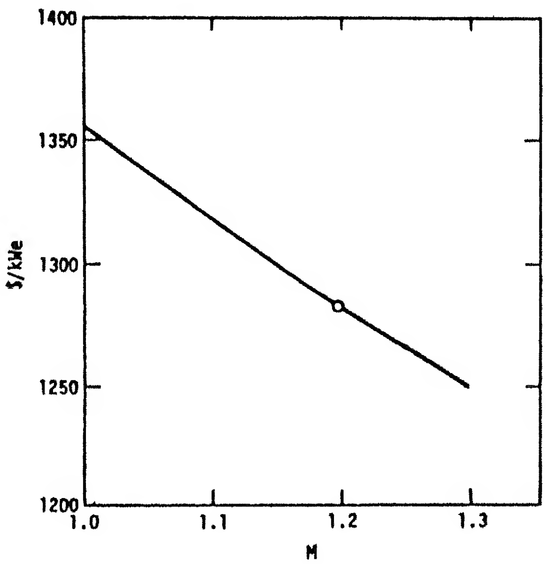

Figure 7

TMR Cost vs Blanket Multiplication

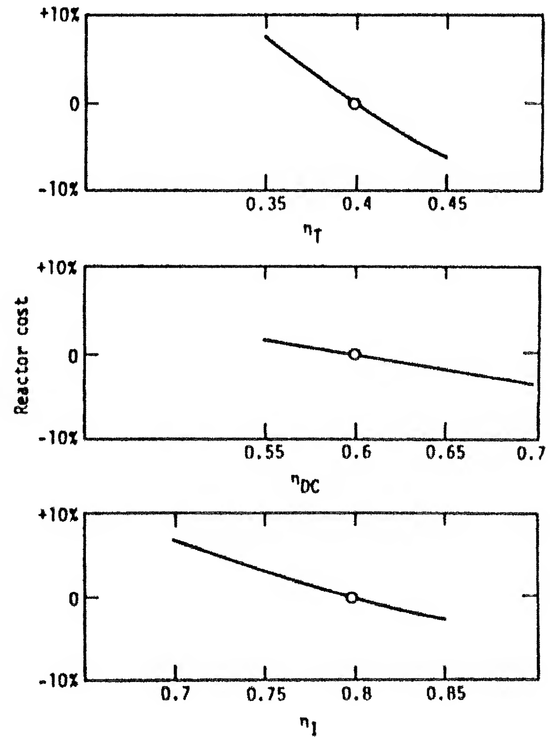

Figure 8

TMR Cost vs Energy Conversion Efficiencies

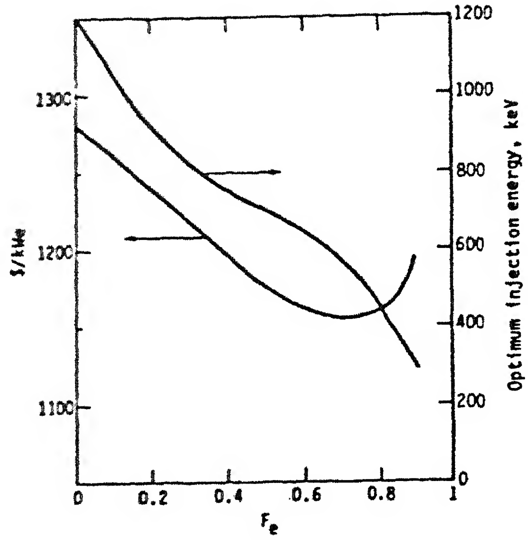

Figure 9

TMR Cost vs Fraction of Heating Direct to Electrons

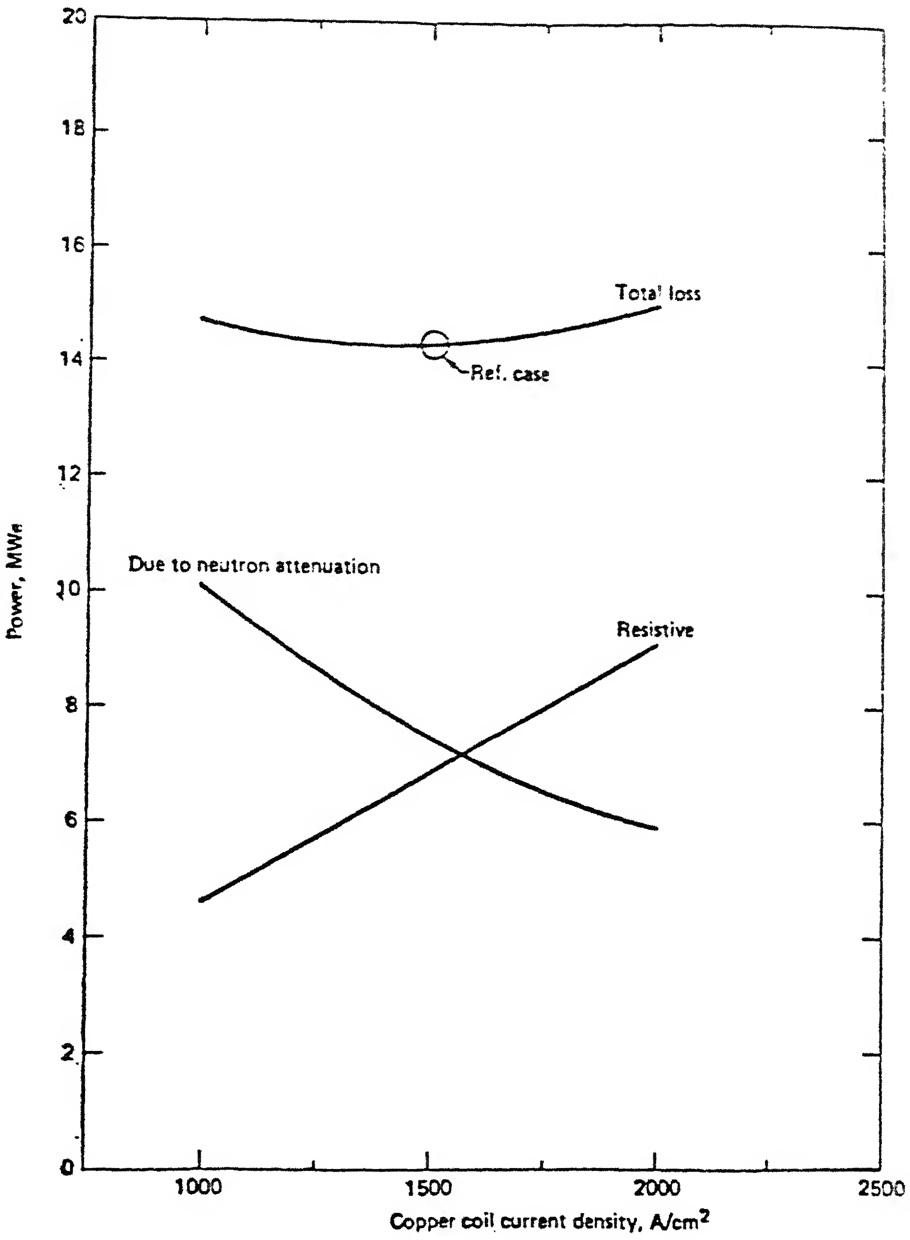

Figure 10

Parametric study of FRM reactor as a function of coil current density

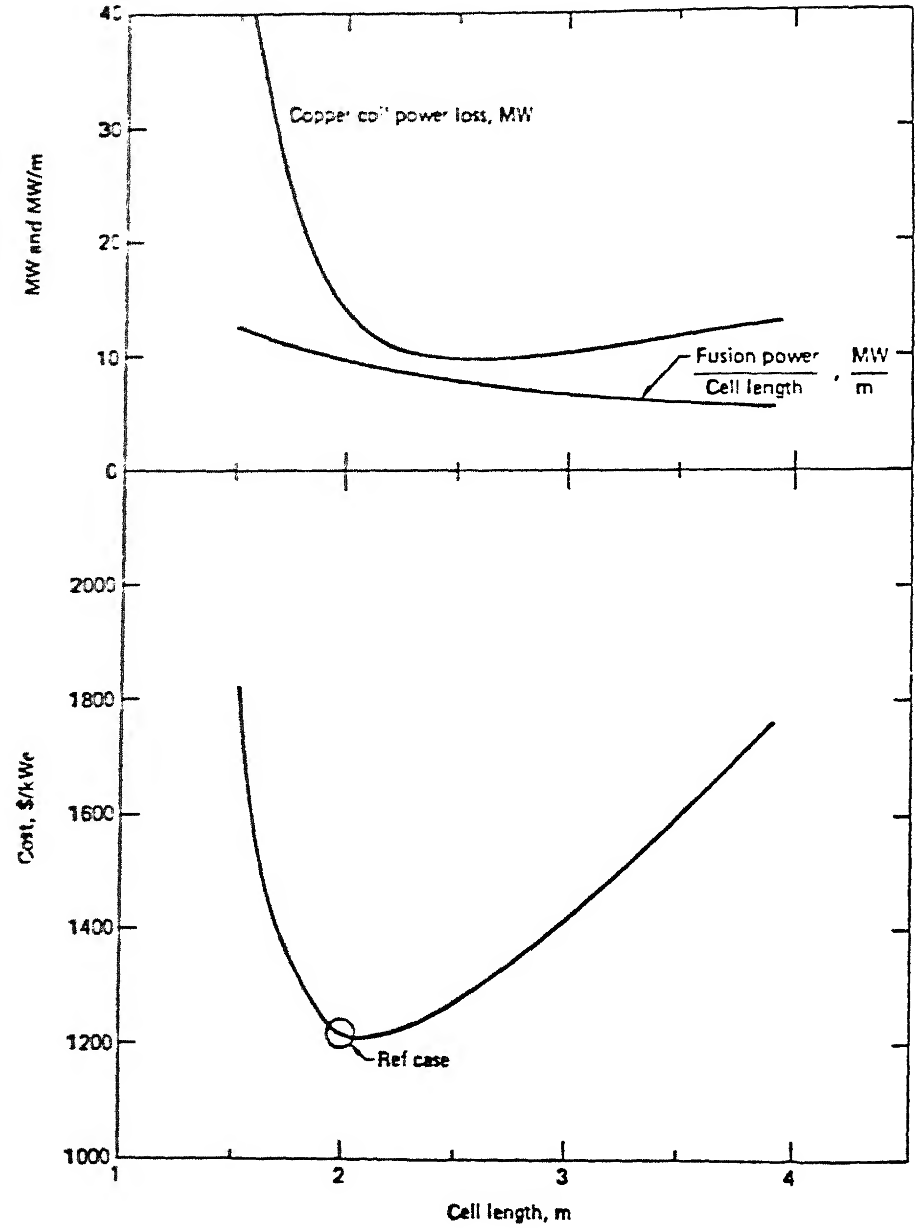

Figure 11

Parametric study of FRM reactor as a function of cell length

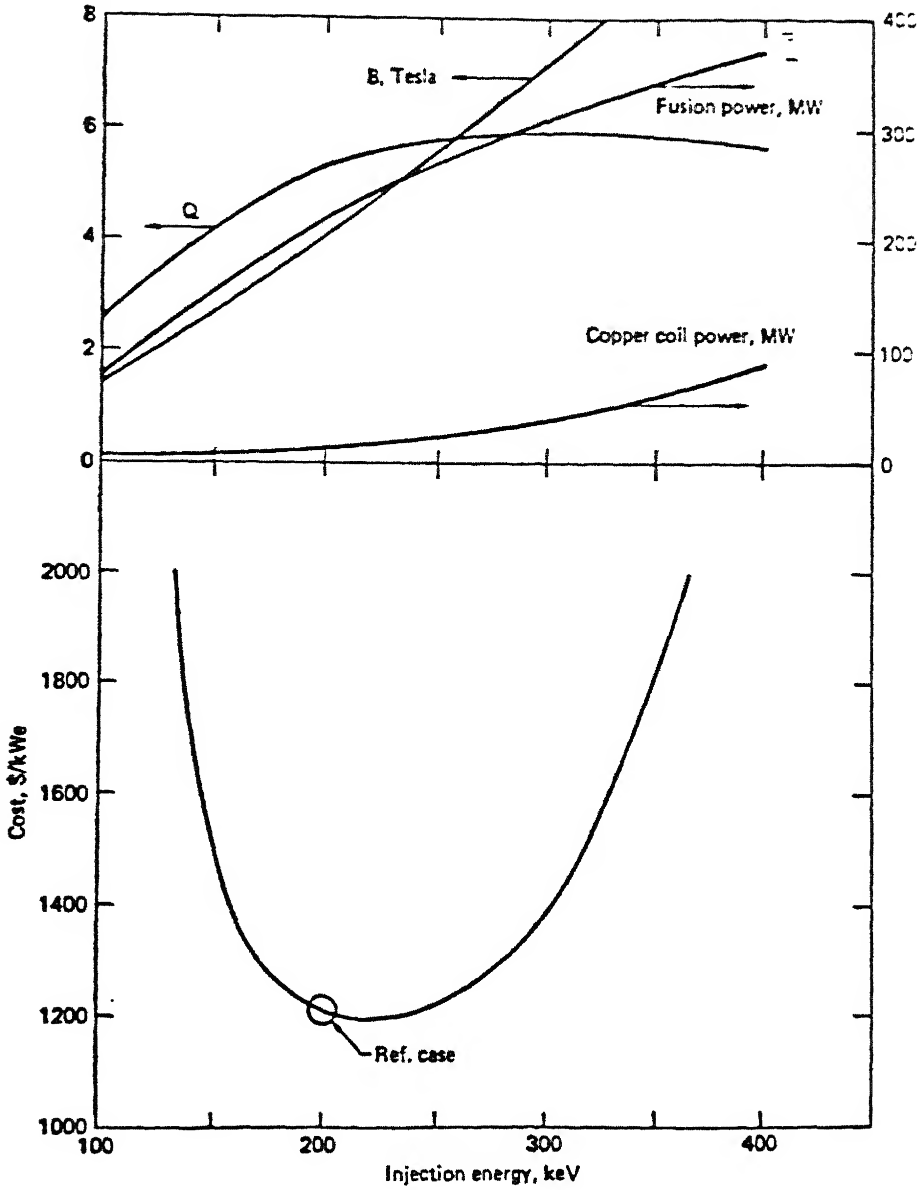

Figure 12

Parametric study of FRM reactor as a function of injection energy

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II.

AN ASSESSMENT OF THE DESIGN STUDY OF THE 1 MeV NEUTRAL BEAM INJECTOR REQUIRED FOR A TANDEM MIRROR REACTOR

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An Assessment of the Design Study of the 1 MeV Neutral Beam Injector Required for a Tandem Mirror Reactor

I. Introduction

During 1977 in conjunction with the review of the TMX proposal, the Advanced Fusion Systems Branch recommended that the Office of Fusion Energy should initiate a study of the suspected problems associated with neutral beams with energies in the range of 1 MeV which will be required for Tandem Mirror Reactors. During FY 1978 the System Studies Program at Lawrence Livermore Laboratory (LLL) has been carrying out such a study budgeted at $125,000. The description of the study is as follows:

> "Conduct a design study of a long-life neutral beam injector for the Tandem Mirror Reactor which could be used for other mirror fusion systems as well. The study shall be an integrated design including mechanical, cryogenic, electrical and material considerations, and emphasizing long-life operation. Special attention shall be given to radiation damage, sputtering, blistering, evaporation and cyclic fatigue."

The design problems and various technical issues connected with such highly energetic high power neutral beams had been under consideration by LLL since 1976 [1,2]. The present LLL study is expected to be completed by July 1978.

II. Background

The neutral beams which are presently used in fusion related experiments are formed by neutralizing positive ions extracted from a plasma source and accelerated to the desired energy. In these devices neutralization is attained through charge exchange in a gas or vapor cell. The efficiency of neutralization based on this technique falls off very rapidly as the ion energy exceeds 100-200 keV range. At 1.2 MeV, less than 0.04% of an atomic deuterium ion beam is neutralized in a gas cell. Hence, the presently familiar positive ion-based neutral beam technology cannot be simply extended to MeV ranges.

It is possible, however, to use similar positive ion technology by accelerating molecular clusters and breaking them while neutralizing. But they will have to be accelerated to a much higher energy before neutralizing. Accelerating D_2 to 2.4 MeV and neutralizing yields a 10% efficiency or accelerating D_3 to 3.6 MeV and neutralizing yields a 23% efficiency in the production of a 1.2 MeV D^o beam[2/]. However, these high voltages introduce proportionately higher electrical breakdown problems.

If negatively charged ions are used, it would require an accelerating voltage of $\sim$ 1 MV to produce $\sim$ 1 MeV beams. However, the technology

based on negative ions will have to be further developed even to test the feasibility of producing a 1.2 MeV, 147 MW D^0 neutral beam system which is required for the TM reactor.

III. Preliminary Studies of Negative Ion Based Neutral Beams

The preliminary studies[2/] carried out at LLL revealed many relevant issues which, in fact, form the basis of the present study. The neutral beam system consists basically of

- a negative ion source
- an "accel region" where the ions are accelerated to the desired energy
- a neutralizing region where negative ions are neutralized.

The design of the accel region is fairly straight forward. However, there are many choices for the design of both the ion source and the neutralizing region.

There are basically two techniques to produce negative ions, namely, 1) charge exchange method and, 2) direct extraction method. These methods[3/] are summarized in Table 1. Even though none of these methods are fully developed and can meet the requirements of a 1.2 MeV source, based on gas efficiency, optical quality of the beam and prospect for continuous operation, LLL has chosen the double charge exchange method using cesium in the present designs. Another reason for using a cesium

cell is that it acts as a gas curtain to block the flow of low temperature neutral gas streaming out of the source region into the accel region and as a result the gas in the accel region can be pumped independently.

IV. Conceptual Design of the Ion Source

The basic principle is to generate a beam of positive deuterium ions, accelerate them to 1 keV and transmit them through a cell containing a cesium plasma. The ions undergo charge exchange resulting in the formation of negative ions which then enters the accel region.

The ion source is a cathode made of two impregnated tungstem emitters mounted face-to-face and its design features[4/] follows those of the LBL/LLL source for positive ion generation. A three grided assembly, the design of which has been recently completed as part of the ongoing study program at LLL, extracts the ions and delivers 1 keV positive ions into a cesium double charge exchange cell. The discharge consumes a total of 1.54 MW (including filament power) to produce 800 amperes of positive ions. The gas pressure at the cathode is kept at 10^{-2} Torr which it is brought below 2×10^{-3} near the cesium cell by adequate pumping. The positive ions undergoes charge exchange in the cesium cell producing about 155 A of D^-.

V. The Charge-Exchange Cell

The preliminary design of the charge-exchange cell incorporates a jet with extremely low loss of the cesium. Thus cesium contamination should not be a problem but this assumption must be verified experimentally. The ongoing study shows that an eutictic of sodium and cesium which has a melting point of -30°C is better than pure cesium. A new nozzle design also permits better control and recirculation of cesium and sodium.

The positive ion beam extracted from the source is driven through the cell where 20% of it becomes negative ions and the rest remains as positive ions. Only the negative ions undergo further acceleration. As a result a gas-load equivalent to 80% of the beam extracted from the positive ion source will have to be pumped away by the cryopump panel surrounding the beam line. Calculation shows that the cryopumps must handle a gas-load of 106 Torr.l.s^{-1}. Two 5m x 5m walls of cryopanels should be capable of handling this gas-load even with the additional restrictions created by the electrostatic shields so that a base pressure of 10^{-4} Torr can be maintained. If such a pressure can be maintained in the region where the negative ions pass through, the loss of negative ions due to collisions with the neutrals can be kept below a few percent and the overall efficiency of producing the 1.2 MeV negative deuterium ions entering the stripping cell from the positive ions extracted from the cathode would be about 19%.

VI. The Stripping Cell and Drift Tube

A cell containing cesium vapor, cesium plasma or a large flux of photons with energy greater than the electron deuterium binding energy can be used as a stripping cell. The advantages and disadvantages are listed in Table 2. Since a gas cell will put an unreasonable burden on the pumping system and since the photo-detachment process requires prohibitively high power density optical radiation, the preliminary study[2/] emphasized the use of a cesium plasma in the stripping cell. Cesium is produced by heating cesiated tungsten sheets. The cell was chosen to be 200 cm deep and the plasma density to be $\sim 10^{13}cm^{-3}$. The flow of cesium from the cell to the ion source or to the reactor was thought to be preventable by the application of a transverse magnetic field of about 0.1T.

The background gas pressure beyond the stripping cell is to be maintained at 10^{-5} torr or less by adequate pumping so that the loss of neutral beam power in a 10m drift tube will be negligible (less than 1%).

VII. The Accelerator Column

There are three conflicting issues that confront the design of the accelerator column. They are 1) requirements of ion optics, 2) pumping, and 3) reliable high voltage insulation.

The extraction grids are 40% transparent with hollow molybdenum laterals, cooled to 500°C by a flow of liquid metal. Two large vacuum ducts connected to two mercury ejector pumps evacuates this region. Since the breakdown across a series of low voltage gaps is less likely than across a single high voltage gap, electrostatic shields are introduced at various intermediate potentials between the high voltage potentials and ground. Pumping efficiency is maintained by making these shields at least 80% transparent. By forming shields out of many small sections and isolating them by resistors to impede the transfer of energy from section to section, catastrophic arcs in this region could be prevented. Auxiliary components and lead wires are to be surrounded by high pressure SF_6 gas, shielded from neutrons and gamma flux to prevent electrical breakdown.

VIII. Technical Issues Revealed

- The most serious problem is the possibility of electrical breakdown and formation of catastrophic arcs in the high voltage region of the accelerator.

  The presence of cesium in the system can give rise to electrical breakdown. There is a possibility of at least small quantities of Cs reaching the accelerator region. Even one or two monolayers of cesium on the grid structure can cause electrical breakdown.

- A more detailed analysis of the accelerator grid structure showed that the spacing between the electrodes should be increased to more than what was originally planned for convenience in repair and maintenance. But, this would increase beam loss as well as the problems arising from the stripped electrons left in the wake of the beam. Consequently, pumping will have to be made more effective.

- The high voltage feed-throughs and insulators, when subjected to the neutrons and alpha-particles which escape from the reactor, may not withstand large potential gradients.

- A gas load equivalent to 80% of the beam extracted from the positive ion will have to be pumped away from the accelerator region close to the charge-exchange cell. No matter how fast the pump works, the effective gas pressure in the central region where the negative beam passes through cannot be zero.

- A closer look at the stripping cell using a cesium plasma shows that it has severe limitations. Shielding this region from the powerful magnets of the reactor will not be easy. Leakage of cesium from the hot plasma region to other parts may not be absolutely preventable.

- The energy stored in the interelectrode capacitance at the high accelerating voltages can be very large and care must be taken in the design of the grid structure so that they could withstand the arcs.

- Separating D^- and electrons in the accel region could also be a problem. Since electrons are loosely bound to the deuterium atoms, any attempt to separate electrons might also detach electrons from the negative ions.

IX. Conclusions and Recommendations

The present studies have revealed most of the important problem areas in the design of a negative ion-based neutral beam source. Extensive programs and detailed experimental studies in these areas are now needed. Since the availability of neutral beams with energies higher than 200 keV is a must for mirror reactors, an accelerated program to investigate the various identified problems is warranted. This accelerated program would necessitate an increased budget beyond what is presently planned for the next several years.

In view of the many complexities associated with the neutral beam sources, alternate heating techniques such as RF heating of ions or electrons which would reduce the energy and power requirements of the neutral beams should also be pursued.

In order to facilitate the timely availability of the neutral beam sources alternate scenarios for the design of the ion sources and neutralizing

cells should be pursued. It is very possible that cesium will be unsuitable in the system since its tendency to cause arcs is well known. The present status of other methods which do not use cesium are not well developed. The techniques such as direct extraction methods for ion sources and electromagnetic irradiation for detaching electrons should be pursued. The uncertainties, the complexities, the size, and the cost of energetic neutral beam systems can be overcome only by adequate research and development work on the design and evaluation of the components. Only then is it possible to establish the economic and technical attractiveness of mirror fusion reactors using 1 MeV neutral beam injector systems.

TABLE 1

NEGATIVE ION PRODUCTION

CHARGE EXCHANGE

METHOD	R & D ACTIVITY	COMMENTS
1. DOUBLE CHARGE-EXCHANGE	LLL/LBL, KURCHARTOV, GRENOBLE	CESIUM GAS CELL SODIUM " " CESIUM " " + GUIDE MAGNETIC FIELD
2. CLUSTERS CHARGE-EXCHANGE	KARLSRUHE	CLUSTERS-BREAK UP AND CHARGE EXCHANGE IN CESIUM

DIRECT EXTRACTION

METHOD	R & D ACTIVITY	COMMENTS
3. MAGNETRON AND PENNING SOURCES	BNL, NOVOSIBIRSK, LASL, FERMI, ORNL	CESIATED SURFACES IN PLASMA.
4. LASER - E-BEAMS ON HYDRIDES	TRW	MECHANISM NOT KNOWN
5. VOLUME PRODUCTION	ECOLE POLYTECHNIQUE	MECHANISM NOT KNOWN
6. SURFACES	ORNL, LLL/LBL	POSITIVE IONS ON SURFACES FUNDAMENTAL STUDIES

Table 2

Possible Stripping Media

Stripping medium	Advantages	Disadvantages
Gas or vapor	Simplicity.	Maximum conversion 60% to 65%.
		Energetic D^+ formed by ionization.
	Low power requirements.	Gas or vapor used near fusion experiment.
Plasma	Conversion efficiency = 80%.	High ionization required.
		High power requirements.
		Energetic D^+ formed by ionization.
		Gas or vapor used near fusion experiment.
Photon	No D^+ formed.	High (advanced) technology.
	Conversion efficiency arbitrarily high.	
	No additional gas or vapor used.	High power requirements.

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III.

THE SIGNIFICANCE OF THE RADIAL PLASMA SIZE MEASURED IN UNITS OF ION GYRORADII IN TANDEM MIRRORS AND FIELD REVERSED MIRRORS

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The Significance of the Radial Plasma Size Measured in Units of Ion Gyroradii in Tandem Mirrors and Field Reversed Mirrors

I. Introduction

The plasma parameter S defined as the ratio of the plasma radial scale length R_p to the ion gyroradius ρ_i (calculated using vacuum magnetic field), plays a very important role in determining the stability and the transport mechanism of plasmas confined by magnetic fields. The end plug of the Tandem Mirror (TM) is similar to 2X-IIB geometry. In extensive data base and theoretical understanding have been accumulated on 2X-IIB experiments during the past few years[1,2]. Also the central solenoid of the Tandem Mirror has benefitted from the linear theta-pinch experience[3]. However, the Tandem Mirror, as such, is a relatively new concept and still awaits the first experimental demonstration. The data base for the field reversed mirror (FRM) geometry is very inadequate. Both theory and experiment for FRM are very much underdeveloped. Consequently, a clear evaluation of the significance of the scale length parameter S in the performance of the Tandem Mirrors and Field Reversed Mirrors has to wait for better physics understanding.

The scale length parameter can be used as a design variable in analyzing reactor economics[4]. Of course, the credibility of the reactor design depends on whether the choice of the parameter range is practically realizable or feasible from the physics point-of-view. The experience

with 2X-IIB gives a high degree of confidence in the parameter range chosen for the present Tandem Mirror Reactor designs. However, for the Field Reversed Mirror Reactor design studies, the parameter range of S desired from the reactor economics point-of-view lies in an experimentally unexplored and theoretically ill-understood regime[4/].

The present physics knowledge, nevertheless, is adequate in qualitatively determining the parameter range of S which might be satisfactory. In Tandem Mirror configurations, for example, the radial scale length of the end plug plasma should be made sufficiently large to prevent the most dominant instability mode observed in 2X-IIB experiments, namely, the DCLC mode. As the scale length is increased the drive for the DCLC mode is weakened so that the streaming plasma required[5/] for stability diminishes to insignificance[6/] for scale lengths $S > 40$. Of course, there are engineering and economic limitations in making the scale length very large. On the other hand, in the Field Reversed Mirror configurations, if the ratio of the plasma minor radius, a to the ion gyroradius, ρ_i is made very large, the plasma will be susceptible to MHD instabilities[7/]. From the reactor economics point-of-view it was found to be advantageous to use large values of (a/ρ_i) for Field Reversed Mirrors[4/], which would still meet the plasma stability requirements.

Since the physics of the field reversed plasma is underdeveloped, the reactor studies have been based on an assumption that the plasma remains stable in the parameter range of (a/ρ_i) up to 10. In the following sections we will discus the significance of this scale length parameter as applied to Tandem Mirrors and Field Reversed Mirrors in more detail.

II. Tandem Mirrors

A. The End Plugs

The microstabilities which enhance the losses in the end plugs are:

1. drift cyclotron loss-cone mode (DCLC),
2. Alfven-ion cyclotron mode (AIC), and
3. convective loss-cone mode (CLC).

In 2X-IIB experiments the introduction of warm plasma, via streaming guns or gas feed in the fan region, reduced the ion cyclotron noise and allowed plasma buildup to higher densities. This phenomenon has been explained as due to a partial filling of the loss cone in velocity space with warm plasma[8/]. The amount of warm plasma re-

quired for stability is related to the plasma radial scale length

$$R_p \equiv \left(\frac{1}{n}\frac{dn}{dr}\right)^{-1}$$

measured in units of ion gyroradius ρ_i. Theory predicts that if (R_p/ρ_i) is larger than 40, the plasma will be stable to DCLC mode[6,9]. (DCLC mode is a local phenomenon. Hence, the choice of the radial scale length depends on the rate of change of the plasma density instead of the physical size of the plasma. Such a definition is not meaningful for FRM plasmas where DCLC mode does not exist.) Since injection of warm plasma degrades the quality of the confined plasma, this scale length should be made as large as possible at least in the interior of the plasma to reduce the warm plasma requirements. Ideally, a flat density profile with steep boundary layer stabilized by a warm plasma is preferable.

In the tandem mirror, the partial penetration of the warm Maxwellian ions from the central cell into the plugs is expected to take the place of the warm plasma. However, if the plasma scale length is not sufficiently large, the spill over from the central cell may not be sufficient and auxiliary techniques may have to be used to suppress the DCLC mode in the end plugs.

The Alfven-ion cyclotron mode and the convective loss-cone mode were never observed in 2X-IIB experiments. The velocity space diffusion coefficient due to the convective loss-cone mode is expected to vary

exponentially with the length of the plasma also measured in units of ion gyroradius[10/]. More experiments are needed to establish the effects of these modes.

B. The Solenoid

If the temperature and density of the plasma in the solenoid is uniform, then the plasma should be stable. However, the boundary layer of 2 to 4 ion gyroradii thickness is subject to instabilities driven by density and temperature gradients[11,12/]. The diffusion coefficent is expected to decrease with the temperature gradient scale length also measured in ion gyroradii. The effect of such instabilities of the exterior regions upon the bulk radial diffusion is unclear at present.

III. Field Reversed Mirrors

In the derivation of the scaling laws used for the design studies of the Field Reversed Mirror Reactors (FRMR), the parameter S, defined as the ratio of the minor radius a of the torus to the ion gyroradius ρ_i, is used as an independent variable[4/] in relating the performance of the reactor to various externally controllable parameters such as the plasma density and the magnetic field.* The significance of the parameter S

*The equilibrium and stability of FRM plasma are not local phenomena like the DCLC mode. Hence the choice of the definition is changed to reflect global effects considered.

can be judged from the following relationships extracted from the scaling laws:

- peak plasma density $n_o \propto S^{-2}$,
- peak magnetic field $B_o \propto S^{-1}$,
- plasma $Q \propto S^2$,
- diffusion coefficient $\propto S^{-2}$, and
- particle confinement time $\tau_p \propto S^2$.

However, there exists no conclusive theory or experiment indicating plasma stability for values of S above ~ 5.

The significance of the parameter S in the physics of a field reversed plasma could be analyzed by considering the method of achieving the configuration, the stability of the plasma ring and the transport mechanisms in the plasma.

The field reversed configuration may exist if either the ions are drifting in the magnetic field while the electrons are stationary or if the electrons are drifting while the ions are stationary. The path of the charged particle need not be a simple circle around the center of symmetry. In fact, it might make a number of smaller loops for each complete turn. The lower the number of such loops, the higher will be the current density. Thus, the considerations based on current density implies a small minor radius and a low value of S.

The considerations based on the transport mechanism, however, suggest that the plasma ring should be as fat as permissible so that the particles will tend to stay within the plasma region when they get off course due to collision. This implies S should be as large as possible.

The parameter S plays a very dominant part in determining the equilibrium and the stability of field reversed plasma configurations. Equilibrium calculations[4] in the small gyroradius limits and stability analysis for infinitely long thin plasmas[14] have been carried out. These analyses do not pertain to plasma configurations suitable for a field reversed mirror reactor. Improved equilibrium codes are now under development at LLL, NYU and Cornell. However, it is not evident at present whether such MHD equilibria would correctly describe a plasma of a few gyroradii. Stability analysis is also being carried out at the University of Illinois[15]. The preliminary indications of the University of Illinois study is that the plasma will be unstable for $S \leq 5$. Further studies along these lines are now being carried out at LLL using the superlayer code[16]. Theoretical investigation in this area is greatly needed to understand the physics of the field reversed plasmas. At the present most of the information on the field reversed plasma comes from experiments[17,18].

IV. Conclusions

Since the physics of the end-plugs and the solenoid are better understood, it is possible to estimate the significance of the scale length parameter on the performance of Tandem Mirrors, although a true experimental evaluation is yet to be made.

The conclusion we may draw from the present understanding of the physics of the field reversed plasma is that such a plasma configuration will be stable for low values of S (less than 5) where the plasma has limited reactor potential. For the parameter range of S larger than 5 where the plasma exhibits strong reactor potential, a clear evaluation of the significance of the parameter S in determining the equilibrium and stability has to wait for more detailed studies.

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IV.

PRODUCING FIELD REVERSED MIRROR PLASMAS BY METHODS USED IN FIELD REVERSED THETA PINCH

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Producing Field Reversed Mirror Plasmas by Methods Used in Field Reversed Theta Pinch

I. Introduction

The present field reversal experiments at the Lawrence Livermore Laboratory (LLL) are concentrating on slowly building up field reversing plasma rings by injecting energetic neutral beams off axis into a target plasma located at the minimum of a magnetic mirror well. If the "slow build up" method proves to be unsuccessful, additional pulsed high current density ($1\ kA/cm^2$) neutral beam sources are planned to be used in conjunction with the conventional sources to achieve field reversal.

Reverse field theta-pinch experiments in the U.S.[1/], Germany[2/], and the Soviet Union[3/] have produced field reversed plasmas. In these experiments an initial magnetic field is trapped in a plasma which is then compressed and heated by a fast rising axial and oppositely directed magnetic field produced by a single turn theta-pinch coil. In general, the plasma produced in this manner is long and thin (with minor radius of a few ion gyroradii) and lasts at the most for a few tens of microseconds. This plasma, at least in principle, can be used a target plasma for energetic neutral beam injection. However, it is not simple to provide ports for neutral beams in a theta-pinch coil since the driving field can easily be distorted in so doing. An alternate method would

be to move the plasma along the axis to a region where it could be then sustained by neutral beams. This procedure also may have some engineering problems. The magnetic field coils to be used for translating the plasma and the theta-pinch coil can interfere with each other. Consequently, it would be simpler if the plasma can also be translated by the same theta-pinch coil used for its production. This can be done by means of conical theta-pinch coils[4/]. An alternate method of producing a field reversed plasma ring similar to the one produced by conical theta pinch is by means of plasma guns[5/]. These are discussed in the following section.

II. Conical Theta-Pinch Guns

The diverging magnetic fields from a pulsed conical coil not only produce a field reversing plasma ring, but also eject it rapidly from the cone. If two such guns are located at the opposite ends of a magnetic mirror, the ejected rings would magnetically attract each other and combine (assuming the plasma currents are in the same direction). Plasma rings can be thus "stacked" at the minimum of a mirror well and be heated and sustained through neutral beam in jection away from the theta-pinch coils.

III. Coaxial Plasma Guns

Plasma rings can be produced by coaxial plasma guns and translated to the minimum of a magnetic mirror well. The magnetic flux lines of

the plasma gun and that of the mirror form a magnetic cusp. The plasma ring first drifts into the cusp region then "pushes" through the cusp field and enters the mirror well. As in the case of the conical theta pinch two such plasma guns can be mounted at the opposite ends of a magnetic mirror and several plasma rings can be stacked in the mirror well.

IV. Rapid Pulsed Yin-Yang Coils

The idea of pulsing a Yin-Yang coil and compressing a plasma as it is done in a theta pinch is appealing. However, there are severe engineering problems associated with it. The large inductance of a Yin-Yang coil makes the rise-time of the pulse too long. In the 2X-IIB experiments, the rise-time is about 500 microseconds. A strong circulating current in the plasma cannot be induced on this long a time scale . The theta pinch rise-times are on the order of a few microseconds. Thus if the rise-time is to be reduced to, say, 10 microseconds, the capacitance should be reduced by 2500. To keep the energy the same, the applied voltage should be increased by a factor of 50. Consequently, the Yin-Yang coils should be designed to withstand many megavolts as compared to the 60 kV rating of the 2X-IIB coils. The high power switching at megavolt ranges also deserves particular attention. The second problem would be associated with the enormous mechanical strain the coils would undergo on pulsing.

The inductance of the coil can be reduced only by reducing the size of the coils. But that would restrict accessibility of the neutral beams. Based on these practical problems, pulsing Yin-Yang coils to produce a field reversed configuration by inducing a current in a plasma already immersed in a steady magnetic field is very unattractive.

V. Conclusions and Recommendations

The conical theta pinches and plasma guns are interesting concepts for producing plasma rings of sufficiently high density and temperature in a geometry suitable for further irradiation by energetic neutral beams. The technologies associated with both methods are well understood and designing a system suitable for the investigation of the field-reversed mirror plasmas is possible. However, between the two methods, the plasma guns are more efficient and are capable of producing purer plasmas. Hence, the plasma guns should be recommended to be used before the conical theta pinches for producing plasmas for field reversal experiments. Rapidly pulsing Yin-Yang coils involve many engineering problems and, hence, this technique is not very attractive in producing a field reversed plasma configuration.

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V.

RF STOPPERING OF MIRROR CONFINED PLASMAS

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RF Stoppering of Mirror Confined Plasmas

I. Description of Principles

When an RF electric field is applied in a direction perpendicular to a magnetic field, the combined effect of the electric field and the spatial variation of the magnetic field is such as to exert a force on a charged particle in the direction of decreasing magnetic field. At plasma densities sufficiently low that the vacuum fields describe the RF fields, this force may be expressed 1/ as

$$\underline{F} = -\underline{\nabla}\phi \tag{1}$$

where ϕ is a potential function defined as

$$\phi = (qE^2/4m)\ (\omega^2 - \omega_c^2)^{-1} \tag{2}$$

Here q and m are the charge and mass of the particle; $\omega_c = qB/mc$ is the cyclotron frequency; ω and E are the frequency and intensity of the externally applied RF field. When the plasma density is very low and collisions between particles can be neglected, RF stoppering process can be explained by considering the motion of a single charged particle in the magnetic field. The linearly polarized electric field of the incident RF field can be considered to be made up of two circularly polarized field, one rotating in the same direction as the charged particle and the other in the opposite direction. As the particle moves

from the region of weak magnetic field to the coil throat, it quickly gains energy in the region where $\omega = \omega_c$. Consequently, its velocity in the direction perpendicular to the magnetic field increases rapidly causing the particle to reflect back. The phase relationship between the circular motion of the particle and the rotation of the electric field thus changes and the energy gained by the particle before the reflection is now rendered back to the RF field. In the absence of collisions this process is adiabatic. However, if the particle undergoes collision with other plasma constituents during the process, the energy lost in the collision process is not returned to the RF field. Since collision increases with plasma density, RF stoppering ceases to be an adiabatic process at high densities. Further, when the plasma density increases, the collective effects brought about by the dynamic screening action of the plasma becomes important. The singularity of the potential function at the cyclotron frequency disappears giving rise to a new resonance structure for the potential function at a frequency corresponding to the eigenmodes of the plasma [2/].

Theory predicts [2/] that the plugging efficiency improves with higher RF field strengths and higher magnetic fields. It also predicts that the plugging efficiency becomes worse with increaseing plasma density.

II. Experimental Observations

The Institute of Plasma Physics of the Nagoya University, Japan, has had an aggressive experimental program in RF plugging for the past several years [3-5]. The experiments confirmed [6] the theoretical predictions for densities below $10^{12}cm^{-3}$. In these low density regimes RF power was coupled to the plasma through electrostatic modes and in the higher density regimes (up to $10^{14}cm^{-3}$) an electromagnetic coupling was found to be more effective [7].

The experimental results on stoppering a line cusp showed that the RF field intensity required to keep the loss rate constant increases with ion density [6]. Applications of extremely strong RF fields to a plasma results in increased particle heating. In fact, the increase in particle confinement time observed in an RF plugging experiment in a mirror-confined plasma at the University of Tsukuba, Japan, could be explained purely on the basis of ion heating [8] and the phenomenon of RF plugging was not distinctly observed. It should be pointed out that the improvement in confinement times observed when the plasma ions are heated is a bulk phenomenon where as RF plugging is a localized phenomenon occurring near the mirror throats where a gradient in the magnetic field exists.

III. Conclusions and Recommendations

The RF stoppering principles, confirmed experimentally and theoretically in the low density regimes are not strictly applicable in the high density

regime which is of interest to nuclear fusion programs. In the high density regime, very high RF fields are needed which result in ion heating [5/] along with the RF plugging. Despite the obvious advantages RF plugging may offer, there exists very little experimental data to confirm the theoretical predictions in the density ranges above $10^{13}cm^{-3}$. In this regime not only does the theory becomes vague but the experiments become complicated. Collective plasma effects and RF induced heating are among the key questions needing further elucidation. There are possibilities of significant amplification of RF force by the fields near resonance and the penetration of the RF fields into the plasma through some ion wave modes. These are presently addressed in Japanese RF plugging experiments. Development of RF coupling fixtures which are compatible with mirror reactors is yet to be done. It is also possible to use internally excited RF fields, i.e., due to beam plasma instability, instead of an externally applied RF field.

The difficulty associated with RF plugging has been three-fold.

1. The power loss at the electrodes, walls, etc., is high.
2. The field required at high densities is so high that breakdown is a problem.
3. The field required tends to be high and energy is lost in excessive heating of the plasma.

There may be an added advantage in heating the plasma, particularly in generating low energy ions; this may tend to suppress the DCLC instability in a mirror confined plasma.

In view of the little experimental evidence confirming theoretical predictions and the difficulty of theoretical treatment at densities which are of interest to fusion research, it is not very clear whether suitable RF stoppering can be achieved for controlled fusion.

The Institute of Plasma Physics of the Nagoya University has a very aggressive program on RF plugging. Since the researchers in our country can very easily collaborate with the researchers at this institute, my first recommendation is to promote the collaboration.

Under this arrangement it would be very cost effective and beneficial for the U.S. Mirror Program to aggressively pursue a theoretical program on RF plugging.

It may be that these two endeavors will suggest that the U.S. Mirror Program generate data on its own experimental devices; for example, the Japanese data may not be applicable to the specific geometries of the U.S. mirror machines. According to the present plans, there will be several laboratories in the U.S. engaged in RF heating of mirror-confined plasmas within the next few years. It should therefore be easier to develop the RF plugging capabilities in these laboratories at a later time.

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